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## *A Report to the United States Senate and the U.S. House of Representatives*

Subcommittee on Science, Technology and Space
Committee on Commerce, Science and Transportation
United States Senate

Subcommittee on Space Science and Applications
Committee on Science, Space and Technology
U.S. House of Representatives

(NASA-TM-108141) EXPENDABLE LAUNCH VEHICLES TECHNOLOGY: A REPORT TO THE US SENATE AND THE US HOUSE OF REPRESENTATIVES (NASA) 47 p

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National Aeronautics and Space Administration
Office of Aeronautics, Exploration and Technology
Office of Space Flight
Washington, D.C. 20546

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20546

Reply to Attn of L:VJS:brb

JUL 31 1990

Honorable Robert A. Roe
Chairman
Committee on Science, Space
and Technology
House of Representatives
Washington, DC 20515

Dear Mr. Chairman:

Enclosed is a report on Expendable Launch Vehicles (ELV) technologies prepared in response to the Commercial Space Launch Act Amendments of 1988, P.L. 100-657. We apologize for the lengthy period which has been required to develop this report, but hope this material will be useful to the Committee as this important issue continues to be discussed.

Please feel free to contact us if the Committee requires any further information on this subject.

Sincerely,

Martin P. Kress

Martin P. Kress
Acting Assistant Administrator
for Legislative Affairs

Enclosure

cc: Honorable Robert S. Walker

NASA

National Aeronautics and
Space Administration

Washington, D.C.
20546

Reply to Attn of L:VJS:brb

JUL 31 1990

Honorable Ernest F. Hollings
Chairman
Committee on Commerce, Science
and Transportation
United States Senate
Washington, DC 20510

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Acting Assistant Administrator
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Enclosure

cc: Honorable John C. Danforth

# Summary

As directed in Public Law 100-657, "Commercial Space Launch Act Amendments of 1988," and consistent with National Space Policy, NASA has prepared a report on a potential program of research on technologies to reduce the initial and recurring costs, increase reliability, and improve performance of expendable launch vehicles for the launch of commercial and government spacecraft into orbit.

The report has been developed in consultation with industry and in recognition of relevant ongoing and planned NASA and DoD technology programs which will provide much of the required launch systems technology for U.S. Government needs. The report identifies additional efforts which could be undertaken to strengthen the technology base. To this end, the report is focused on needs for launch vehicle technology development and, in selected areas, includes verification to permit private-sector new technology application at reduced risk. If such a program were to be implemented, it would entail both government and private-sector effort and resources.

The additional efforts identified in the report would augment and not replace, the existing launch vehicle technology programs. The additional efforts identified in the report have not been funded, based upon agency assessments of relative priority vis-a-vis the existing programs. Throughout the consultation and review process, the industry representatives stressed the overriding importance of continuing the DoD/NASA Advanced Launch Development activity and other government technology programs as a primary source of essential launch vehicle technology.

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CHAPTER 1

# Background and Introduction

Section 10 of Public Law 100-657, "Commercial Space Launch Act Amendments of 1988," directed that NASA, "in consultation with representatives of the space launch and satellite industry, design a program for the support of research into launch systems component technologies, for the purpose of developing higher performance and lower cost United States launch vehicle technologies and systems available for the launch of commercial and Government spacecraft into orbit."

The accompanying committee reports state that a major purpose of the legislation is "to ensure the successful development of a competitive domestic expendable launch vehicle (ELV) industry." They stress the importance of the industry to national space efforts and to continued U.S. aerospace preeminence. They also state the belief that a continuing research and development (R&D) program in launch vehicle technologies will be beneficial to government and commercial operators and is essential to the maintenance of a competitive domestic launch industry. The reports cite NASA's aeronautics research and technology (R&T) program as a model for the desired long-term program in launch vehicles.

In addition to technology, P.L. 100-657 addresses a number of other issues affecting commercial launch activities, including private acquisition of government property and services, liability insurance, scheduling of government and commercial payloads on commercial launch vehicles at government launch sites, and fairness in commercial space international competition. This NASA report, however, is confined to the R&T question put forth in Section 10. Appendix A reviews progress on several policy and administrative actions relative to suggestions by the Department of Transportation's (DoT) Commercial Space Transportation Advisory Committee (COMSTAC). As in the aeronautics model, systems development by either industry or government entails far greater investment than does R&T. The availability of proven technology does not eliminate the need for large development investment. However, it reduces the development risk and increases the likelihood of success.

This report has been developed in consultation with appropriate representatives of industry, DoD, and other involved government agencies. The primary emphasis is on ELV technology for major system cost reductions as well as improvements in performance, reliability, and launch operations economy. It includes consideration of transfer vehicles required to deliver payloads to geosynchronous or geostationary orbits. If approved, the program would complement--not duplicate or replace--related NASA and Air Force ongoing or planned activities.

CHAPTER 2

# ELV Overview

This overview is provided as a review of the commercial ELV industry evolution and the government/industry relationships which affect the application of new technology to current and future ELV developments.

The National Space Policy announced by the President in November 1989 sought to encourage development of the commercial launch industry by directing U.S. government agencies to: make national ELV properties and services available to the commercial sector on a reimbursable basis; avoid government competition with commercial launch providers; require the use of commercial space transportation services for government programs to the maximum extent feasible; promote international free and fair trade practices; and support R&D for future space transportation.

The post-Apollo space developments which preceded establishment of the National Space Policy included a number of changes in launch vehicle strategies. In the late 1970s a decision was made to phase out ELVs and rely solely on the Space Shuttle for launch capability. By 1983 the transition was nearly complete; the government ceased ELV procurement and the launch vehicle manufacturers discontinued ELV research, development, and production. However, subsequent policy decisions and legislation have restored the ELV as a significant component of the national launch capability.

In 1985, Congress approved the Complementary ELV (CELV) program to provide an alternative to the Shuttle for high-priority military payloads and also authorized conversion of decommissioned Titan II Intercontinental Ballistic Missiles (ICBMs) for use as space launch vehicles. Martin Marietta won the CELV competition with the Titan IV and was also awarded a contract to modify Titan IIs.

In the aftermath of the 1986 Challenger and Titan 34D accidents, a reassessment of national space transportation needs led to establishment of a mixed fleet launch strategy (Space Shuttle and ELVs) to support both military and civil government missions. Commercial payloads not requiring the unique capabilities of the Shuttle were removed from the manifest. The DoD expanded the Titan IV program to accommodate critical payloads off-loaded from the Shuttle. In 1987 McDonnell Douglas was awarded the Air Force Medium Launch Vehicle (MLV) contract for Delta II vehicles to support the launch of Global Positioning Satellites (GPS). The MLV II was awarded to General Dynamics in 1988 for Atlas II vehicles to support Defense Satellite Communications Systems launches.

A NASA space transportation study conducted after the Challenger accident concluded that a robust and balanced mixed fleet is necessary for resilient U.S. civil space operations, increased access to space, and enhanced mission flexibility. The NASA mixed fleet launch strategy, established in 1987, seeks to ensure the availability of a range of ELVs to complement the unique attributes of the Shuttle for approved civil government missions. NASA rescheduled to ELVs four Shuttle payloads that were displaced or would have faced lengthy delays after the Shuttle's return to flight. In 1988 NASA awarded the U.S. government's first commercial ELV launch services contract to General Dynamics to support the launch of National Oceanographic and Atmospheric Administration (NOAA) Geostationary Operational Environmental Satellites (GOES).

By current national policy directives, NASA is precluded from maintaining an ELV adjunct to the Space Shuttle Program and is further directed to purchase launch services from the private sector to the maximum extent feasible or through the DoD. NASA is procuring commercial launch services competitively in three launch vehicle performance classes: SELV (small ELV -- e.g., Scout); MELV (medium ELV -- e.g., Delta II); and IELV (intermediate ELV -- e.g., Atlas I/II, Titan III). Large ELV class (e.g., Titan IV) vehicles are not presently available commercially and will be procured through the Air Force.

Additional details regarding these Air Force and NASA ELV procurements, and brief descriptions of the vehicles, are contained in Appendix B.

Most of the commercial launch vehicles being produced and marketed by General Dynamics, Martin Marietta, and McDonnell Douglas are variants of the government-developed space launch vehicles. They are being marketed for sale to the U.S. government as well as to domestic and international commercial customers. Each corporation has made substantial corporate investments in its commercial product lines, using available technology to modernize vehicle systems, manufacturing facilities, and launch facilities. However, no major new system developments independent of government launch requirements have been undertaken or announced.

A number of new small ELVs are being developed with private capital to compete with the government-developed Scout launch vehicle. The NASA Scout, a four-stage solid-propellant booster developed in the 1960s to support NASA and DoD small-payload launches, has completed well over 100 launches. Over the past 20 years, it has maintained a 98% reliability. LTV Missiles and Electronics plans to market the Scout commercially. The American Rocket Company, Orbital Sciences Corporation, and Space Services Inc. are among the domestic entrepreneurial companies entering the market for small-class orbital and sub-orbital launches.

Some market projections, including the Department of Commerce's May 1988 report "Space Commerce -- An Industry Assessment", estimate the ELV market demand through the remainder of this century to include between 150 and 250 U.S. and foreign commercial launches involving payloads of 4000 pounds. or more to low earth orbit, and approximately twice that total in the smaller orbital and sub-orbital classes. However, these projections have not yet materialized. In addition to the projected multi-billion-dollar commercial launch services market, Commerce also projects a large associated demand for launch support (e.g., payload processing) operations. One private domestic company, AstroTech, Inc., is currently engaged in providing such services for commercial payload launches.

U.S. manufacturers seeking commercial launch business face serious competition from foreign ELVs -- principally the European Ariane family of vehicles, China's Long March series, the Soviet Union's Proton, and a developing new family of Japanese vehicles. The competing foreign vehicles are not necessarily more advanced technologically, and in most instances they have not yet established success rates comparable to those of the U.S. vehicles. Some of them, however, incorporate state-of-the-art technology and have been designed specifically for delivering payloads to orbit rather than derived from missiles designed to more costly military specifications. They operate, or will operate, from government bases which are well suited for commercial use, at locations which may offer appreciable performance advantages because of more favorable latitudes relative to U.S. launch sites. In short, the foreign launch vehicle companies and their governments are strong competitors now and will be even more formidable in the near future.

In general, the technology being developed in U.S. government research programs for improvement of launch economy, reliability, and performance is relevant both to the government's continuing requirement for economical civil and military launch services and a competitive domestic launch vehicle industry.

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CHAPTER 3

# Review Process

A review team consisting of NASA Headquarters and Center specialists in each of the relevant technical disciplines reviewed ongoing and planned NASA technology programs to identify elements which provide significant ELV technology contributions, and to identify areas in which additional effort could increase the benefits to ELV development. These programs included the Office of Aeronautics, Exploration and Technology (OAET) R&T Base programs in both space and aeronautics, the Civil Space Technology Initiative (CSTI) and Exploration Technology programs, and the Office of Space Flight (OSF) advanced development activities. The team similarly reviewed the Air Force/NASA Advanced Launch Development (ALD) program (formerly known as the Advanced Launch Systems (ALS) Advanced Development program), the National AeroSpace Plane (NASP) program, and existing ELV procurement and development plans. These reviews of ongoing technology programs, an assessment of the ELV technology environment and technology needs, and consultations with the ELV industry and the Air Force formed the basis for the potential ELV program described in this report.

Industry inputs were obtained through several mechanisms. Meetings were held with an Ad Hoc Review Team on Low-Cost ELV Technology organized under the NASA Advisory Committee's Space Systems Technology Advisory Committee structure, the DoT's COMSTAC, and the Space Committee of the Aerospace Industries Association. The Ad Hoc Review Team also received Air Force briefings on relevant ALS technology issues. Additional insight on industry technology needs was obtained during discussions and reviews of Independent R&D activities at major ELV manufacturing and launch facilities.

A draft version of the ELV technology report was presented to each of the committees for review and discussion prior to final draft completion. In addition to the committee interactions, informal meetings and discussions involving individual members of the planning team and industry counterparts provided exchange opportunities during the review period. The draft report was reviewed and coordinated with the Air Force ALS Office, other offices within the Air Force Space Systems Division, and related Air Force and DoD offices in Washington.

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CHAPTER 4

# ELV Technology Environment

Definition of the R&T needs addressed in the ELV report was based in part on the following observations developed in discussions with the ELV industry representatives:

- ELVs will figure prominently in U.S. and world space launch activities not only in the near future, but throughout and beyond the era of the new launch vehicles to be developed utilizing ALD or equivalent technology.

- In general, commercial launch vehicle manufacturers indicate that they are primarily absorbed with near-term orders and survival. They understand that their long-range future success will require continuing technology advancement for competitive cost, performance, and reliability. However, for the present, they indicate that realistic cost, risk, and time considerations limit their ability to incorporate new technology in ongoing commercial production of existing ELVs.

- Incorporation of new technology in modifications or derivatives of existing ELVs could result in appreciable cost reduction, although probably not to a level competitive with totally new systems optimized for low-cost commercial applications.

- Strictly from the standpoint of ELV technology needs, commercial vehicles do not present unique requirements. Differences between commercial and government launch vehicle development approaches and operations, however, may create new requirements with respect to technology validation, transfer, and application.

- The "aeronautics model" has not been directly applicable as an example for NASA support to previous (government-procured) space systems. With respect to its possible application to commercial launch vehicle development, some significant differences are apparent:

  - NASA does not develop aircraft, nor does it have primary mission responsibility for aircraft operations. NASA generates aeronautical technology solely for use by the industry or by DoD and other government agencies. For these reasons, and because U.S. industry bears the full cost of commercial aircraft development, NASA and industry cooperatively pursue the development of selected critical high-payoff, high-risk technologies through large-scale test validation to assure readiness for application.

- Relative to space systems including launch vehicles, NASA's mission does involve development and operation. NASA program offices have in many instances completed the necessary validation of technology as part of their systems development activity. NASA has initiated the CSTI and Exploration Technology programs, which include more focused space technology development and validation effort in areas related to future NASA missions. With respect to commercial development, although the mechanisms for introducing new ELV technology are still evolving, the industry representatives identified the lack of technology validation as an obstacle to successful industrial development of future commercial launch vehicles.

- Ongoing and planned NASA space R&T programs include considerable research on fundamental technologies, methodologies, and computational codes in all of the technical disciplines critical to advanced launch systems development. This research is applicable to expendable as well as reusable vehicles, but does not in the industry's view fully resolve the need for validation of new technologies specifically directed at low-cost ELVs, including the small vehicle category.

- The Joint DoD/NASA ALD program will provide a strong base of available technology for development of new government and commercial ELVs applicable to a family of launch vehicles.

- Additional R&T effort can be identified to go beyond the ongoing and currently planned programs by broadening the focus on longer-range future ELV developments, commercial operations, and smaller payload classes. In view of the likelihood that the larger ELV developments will for many years remain closely associated with government launch requirements, the planning of such additional effort should be thoroughly coordinated with the planning of related NASA and Air Force R&T programs directed at lower-cost and improved responsiveness to national space transportation needs.

- Although technology development and validation can significantly reduce development risk, some industry representatives express the view that, in its present state of early evolution, the commercial launch vehicle industry may have difficulty accepting the risk of incorporating even validated new technology in commercially funded developments.

- Finally, although NASA and industry technologists involved in major NASA space programs have established and maintained close working relationships, the commercial ELV industry is only beginning to recognize the benefits of continual exchange, consultation, facilities usage, and joint projects which characterize successful aircraft industry relationships with respect to aeronautical R&T. The difference can be attributed to the primarily military nature of the early ELV developments, the ELV R&D hiatus beginning in the late 1970s, the much more recent emergence of a commercial industrial sector, and the greater breadth of ongoing government and industry R&T programs in aeronautics. The development of closer relationships along the lines of the aeronautics pattern could benefit both the industry and NASA in the development and application of ELV technology.

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CHAPTER 5

# ELV Technology Assessment

SECTION 5.1

## Overview

The ELV technology assessment resulted in the outline of a set of activities which, if conducted in addition to the existing NASA and Air Force programs, would strengthen the technology base being developed to reduce launch vehicle cost and improve performance and reliability. In addition, it could reduce the risk of applying new technologies in government and commercial development. In the following sections the existing programs relevant to each technology discipline are discussed. Where additional effort has been recommended, the potential activity, and the benefits to be obtained, are summarized.

The DoD/NASA ALD program is the government activity which most directly affects the state of ELV technology for the next decade or two. ALD is a joint DoD/NASA program to define concepts and develop technologies applicable to a family of unmanned launch vehicles. This report is based on the best available current information as to ALD program content, and may require revision as that program evolves. NASA's close working relationship with the Air Force assures the ability to adjust promptly if necessary.

As suggested in Chapter 4, the technologies needed for commercial and government ELVs are very similar, but the industry representatives stressed that the risk of incorporating unproven technology may be prohibitive in commercial systems development. For this reason, and because of the government's increasing reliance on commercial launch services, the potential ELV program includes technology development and, in some instances, validation of critical high-risk technology. If the additional activities were to be implemented, this would require cooperative effort, and resources, on the part of the government and the private sector.

The current space transportation technology programs include considerable effort directed at advanced launch vehicles in general and hence are of value to ELVs. In some areas, the funding of potentially beneficial advances has necessarily been limited because of higher-priority requirements on resources. In preparation of the ELV technology report, activities previously judged to be of lower priority were considered for increased emphasis only where the R&T appeared significantly more important when viewed from the ELV perspective. Fundamental R&T activities such as magnetoplasmadynamic propulsion and photonics have been retained in the R&T Base programs and have not been included in the potential ELV program.

Cost reduction is a primary objective of this examination of ELV technology, and is a major discriminator in establishing research priorities. The OSF's statistics indicate that propulsion, materials and structures, and avionics and operations represent the three technology areas which account for the major percentage of ELV costs, and that the proportions of cost attributable to each of these three technology areas are roughly equal. In identifying R&T needs, equal attention was devoted to each of the areas.

Establishment of specific priorities requires detailed understanding of both the cost impact of individual technology improvements and the associated technology verification. To this end, and as means of evaluating the results of the technology development efforts, the potential program contains a continuing series of systems studies in which launch vehicle concepts, designs, and operations are analyzed to determine cost and technology trades and to identify high-yield technology opportunities. The systems studies would be coordinated with related sub-studies conducted in each of the individual disciplines, and with development studies conducted by other agencies and by industry. A considerable portion of the study effort would be conducted by ELV system and subsystem manufacturers.

NASA space programs involve the launching of high-cost, often one-of-a-kind, payloads. The enabling launch vehicle R&T programs have therefore necessarily emphasized performance and mission success. The potential program places stronger emphasis on cost reduction, including technology directed at reducing manufacturing costs. In addition to the R&T activities defined in consultation with the industry, the planned systems studies permit further identification and assessment of cost "drivers" and definition of specific technology efforts and data bases required to support low-cost ELV design and development.

Preliminary prioritization recommendations, particularly in the propulsion area, were obtained during the industry reviews.

In propulsion, the potential program includes analytical and experimental effort to establish a data base on the effects of tolerances on system performance and cost. It includes the generation and verification of technology which could support development of an advanced liquid oxygen (LOX)/hydrogen engine in the 150,000-pound thrust class. Such an engine has been identified by portions of the industry as important for improved ELV core stages, and the technology also appears applicable to future large orbital transfer vehicles. Systems studies assessing LOX/hydrocarbon lower-cost evolutionary engine designs would be performed, but augmentation of technology programs for this purpose would be deferred pending determination of industry interest in pursuit of the study results.

The propulsion effort would include provisions for technology effort on low-pressure booster systems, with selection of the liquid/liquid or liquid/solid approach dependent on industry booster studies.

The propulsion activity would build on the NASA Solid Propulsion Integrity Program (SPIP), providing for an additional effort to develop a more extensive technology data base for design, manufacture, and inspection of composite motor cases. It would also include improved technology for inexpensive (minimum-test) expendable engine qualification.

NASA will facilitate private sector access to key required test facilities for complementary and cooperative technology projects, and for commercial propulsion system development testing.

In <u>materials and structures,</u> the potential program includes the development of advanced aluminum alloy technology and fabrication processes for cryogenic tanks and elevated temperature applications, extending the technology beyond the current aluminum-lithium alloys proposed for use in the ALD program. Similarly, effort would be directed at new composite materials systems for ELV applications, with emphasis on potential for low-cost processing and fabrication. Also included would be research on new materials for tank insulation and advanced thermal protection systems, cost-effective processing and fabrication methods, and improved design, analysis, and test methods for structural integrity and life assurance to ensure high reliability of ELV structures. These efforts would also include testing of subscale and full-scale components to verify the new technologies.

In <u>avionics and operations,</u> the potential program includes development of technology for onboard closed-loop guidance and control to permit greater tolerance to varying wind conditions and hence reduce launch delay costs. It includes the definition and test of advanced fault-tolerant avionics hardware and software to provide real-time fault management and reliability equivalent to that of highly redundant reusable systems but compatible with the low-cost expendable system objectives. It also includes development of technology for an integrated electromechanical actuator, power, and control system with onboard health monitoring capability, directed at eventual replacement of hydraulic systems in future ELVs.

The report also defines efforts on automation for software development, operations, and training, directed at technology advances which could be introduced during ELV block changes as well as in new development.

In the area of aerothermodynamics, no new efforts specifically directed at ELV technology are defined. NASA does, however, recognize the importance of its unique wind-tunnel and computational fluid dynamics (CFD) capabilities in providing the basis for the aerodynamic, aerothermodynamic, and structural load predictions required for launch vehicle design and operation. These essential tools will continue to be maintained and improved for support of government programs, and for assistance as necessary in generating the data bases required for specific new ELV designs. Frequent interchange meetings with industry to make certain that contractors are kept abreast of technology progress in these areas and that NASA remains current as to new development trends and problems. Cooperative programs with industry would be encouraged to increase industry familiarity with these tools and facilitate their use. As in the aeronautics programs, industry requests for NASA R&T effort on specific development problems would be assessed on the basis of the anticipated research value or contribution to the overall knowledge base.

SECTION 5.2

# Propulsion

Industry decisions as to which propulsion systems may ultimately be needed for commercial launch vehicles will undoubtedly require extensive study and will vary depending on the nature of the application. Ongoing NASA and DoD technology and commercial development programs will contribute significantly to the technology advancements and data bases required for future propulsion system development programs. ELV industry access to the output of these technology programs, use of government research and test facilities, and consideration of industry requirements in the government technology programs could contribute materially to the propulsion systems of the future.

Recent discussions with the launch vehicle industry indicate that propulsion technology advances and augmented data bases are needed to support its design and development of a range of candidate lower and upper stage propulsion systems. These systems, listed in order of expressed priority, include LOX/Hydrogen, LOX/Hydrocarbon, Solid, and Low-Pressure Booster propulsion systems for launch stages; and LOX/Hydrogen, Storable Liquid, Solid, and Hybrid propulsion systems for upper stages. Substantial technology data bases currently exist for these engine families, with the exception of the low-pressure booster systems. The potential augmentations to the ongoing technology programs would strengthen research support for the design and development of low-cost expendable launch systems.

The potential propulsion effort is discussed in the following paragraphs, starting with a description of the approach to low-cost engine design and development technology. Then, for each of the engine classes, the applicable ongoing NASA and DoD programs, and the potential effort to focus increased emphasis on low-cost launch systems, are discussed. The additional effort, if undertaken, would complement current programs. In some instances, the required effort does not constitute new activity but rather additional ELV emphasis in research already planned but not yet implemented.

## Low-Cost Engine Technology

The life-cycle cost elements of any propulsion system, whether expendable or reusable, are the design and development, manufacture, and operation phases. What is sought is the propulsion system that minimizes overall vehicle life- cycle costs, consistent with the performance and operational requirements. An iterative design process that considers and trades the cost of development, manufacture, and operation, in synthesizing the optimum design, can contribute substantially to reducing the life-cycle costs. Technology programs can serve to enhance the life-cycle elements by addressing specific low-cost needs.

An effective approach to low-cost propulsion is to adopt a design philosophy (simpler designs with fewer parts) that accepts less than peak performance, if necessary, to ease the development and manufacturing processes, while making maximum use of standard lower-cost materials and commercial manufacturing processes. The ALD program, which is focused on developing and demonstrating design and manufacturing technologies to achieve low-cost expendable systems, is an example of this approach and should make a major contribution to meeting the propulsion requirements of the ELV industry.

Another approach to lower design and development costs involves the relaxation of tolerances in critical engine components. Tolerance relaxation could lead to significant cost savings as the result of much simpler manufacturing and inspection processes, reduced certification and acceptance testing, and fewer part rejections. Conservative design tradition generally holds that relaxed tolerances lead to compromises in component performance, engine weight, or operating conditions. However, the actual relationship between performance and adherence to strict design and manufacturing tolerances is not fully understood, nor documented. The ELV low-cost engine technology activity would include extensive component-level testing to develop an experimental data base on the real effects of relaxation.

Design and analysis tools being developed in the CSTI program will provide a basis for parametric trade studies permitting identification of the most critical components and a first-order estimate of the impact on performance and weight. The results of these trades would then be factored into the vehicle system studies to establish those engine design approaches that result in minimum overall system costs. The extensive experimental data base, developed at the component and engine system level, would permit verification of the analytical codes and also support subsequent industry low-cost engine design efforts.

The analytical tools to be verified experimentally would include codes to: evaluate the effect of injector element tolerances on combustion performance, stability, and heat transfer; assess the impact of coolant passage tolerances on combustor life; determine the effect of turbine blade configuration and tolerances on flow losses and turbine and pump efficiencies; determine the impact of reduced tolerances in bearings and seals; and assess the effects of tolerances on the structural response and predicted life of the engine components being studied. The experimental data and the verified analyses could establish the feasibility of cost reduction through tolerance relaxation.

## Liquid Oxygen/Hydrogen Propulsion

As expressed in the industry advisory group rankings, high-performance LOX/hydrogen propulsion is the highest-priority need for future system developments. It can be used for all launch vehicle stages, and has also been proposed for a combined second and upper stage configuration. The ALD program addresses low-cost manufacturing processes, design concepts, and development and testing of full-scale critical components including turbopumps, thrust chambers, and gas generators, for large (400,000 to 600,000-pound thrust capability) engines for ALD concepts. Some but not all of the information resulting from this effort will be generally applicable to LOX/hydrogen engines regardless of the intended thrust level.

In some segments of the ELV industry there is a strong interest in a smaller (approximately 150,000-pound thrust class) engine operating on a high-performance engine cycle for combined second-stage and upper-stage applications. Other segments of the ELV industry prefer a near-term alternative to the new-engine approach, favoring for upper-stage applications an upgraded version of the RL-10 engine with somewhat higher thrust and performance. The thrust level would be too low for cost-effective application to a new booster or second stage propulsion system, but the upgrade could provide appreciable Centaur improvement.

The interest in the new medium-thrust engine creates a need for associated technology and an engineering data base which could support development of such an engine including, where required, throttleability, high-altitude ignition capability, and variable mixture ratio. Much of the basic technology for high-performance engines is currently being addressed in NASA's CSTI Earth-to-Orbit (ETO) and Exploration Technology Chemical Transfer Propulsion (CTP) technology programs. These programs are designed to provide new concepts and improved tools for the design and development of minimum-cost launch vehicle, upper stage, and space-based engines. The Exploration Technology CTP program will also produce an integrated breadboard engine in the 5,000 to 50,000-pound thrust class.

Because of the strong industry view as to the importance of the 150,000-pound thrust class propulsion system, and because it could involve very costly development, the technology effort would be similar to that being conducted in the ALD program for the larger thrust engines. It would be directed at establishment of a validated technology base, developed for low-cost systems and components in an experimental engine system design, fabrication, and ground-test program. Expander, split-expander, or gas generator cycle options would be considered, possibly with the added capability to operate over a range of mixture ratios (from conventional hydrogen-rich to oxygen-rich) for selected applications.

Cycle trades permitting selection of one of the three cycles on the basis of performance and cost would be included. Thorough investigation of this system, including a point design with accompanying performance and cooling analyses over the mixture ratio and throttling range, may give rise to additional technology needs not now evident. The approach would be to analyze the system, develop any technologies fundamental to the system that are not being addressed in current programs, such as oxygen-rich combustion and materials compatibility in a high-temperature oxygen-rich environment.The final step would be to perform a detailed system design, fabricate and test components, assemble a breadboard system, and conduct system-level tests to obtain performance and cost data.

## Liquid Oxygen/Hydrocarbon Propulsion

Advanced pump-fed LOX/hydrocarbon engine technology for future large ELVs is included in the ALD program. In addition, evolutionary improvement of LOX/hydrocarbon propulsion is an option for reducing the cost of existing expendable launch vehicles. The LOX/kerosene combination was used in the Saturn vehicles, and is currently used in the Atlas and Delta vehicles. The adaptation of improved LOX/hydrocarbon propulsion systems to Atlas and Delta (to replace both solid and liquid systems), as well as to the Titan family (which currently utilizes solid booster strap-ons and storable propellants for their liquid stages) could lead to reduced operating costs and reduced environmental problems for these already operational systems. General technology support for pump-fed LOX/hydrocarbon propulsion systems is being addressed in NASA's CSTI ETO program. However, specific focus on low-cost evolutionary LOX/hydrocarbon technology for existing ELVs would require redirection and augmentation of the current program to support low-cost design approaches at the engine system level. The vehicle system studies would identify technology needs for this evolutionary approach and can be used as a guide to defining appropriate technology program augmentation if industry proposals indicate a need for such effort. Additional LOX/hydrocarbon activity may also materialize in the area of low-pressure booster propulsion discussed below in the Low-Pressure Booster Propulsion subsection.

## Solid Propulsion Systems

Cost and reliability of current solid propulsion systems represent significant industry concerns relative to both lower and upper stages. Much of the needed technology is presently either being worked in various DoD programs and the NASA SPIP, or has been planned for future efforts in support of U.S. government requirements. The DoD programs are currently focusing on insensitive, high performance, and low signature propellants. The solid propulsion portion of the ALD program is focusing on clean burning, low-cost propellant processing, the development of a non-asbestos insulation, and composite motor cases.

The SPIP, a national program developed in cooperation with DoD and industry, is designed to put in place the engineering capability for improving the success rate of U.S.-built solid rocket motors (SRMs). It is directed principally at improving the science and engineering for materials data bases, design capability, manufacturing, and product verification, and at advancing the community infrastructure and culture. The program is designed to address seven key solid propulsion issues: composite motor cases; propellant and insulation; nozzles; bondlines; combustion dynamics/internal ballistics; joints and seals; and verification testing. Propellant, nozzle, bondline, combustion dynamics, and verification efforts are now under way. The industry indicated that, with added emphasis on composite motor cases for ELV applications, the originally planned SPIP, together with the ongoing DoD programs, would in general satisfy their solid propulsion needs. At present, NASA SPIP planning does not include the composite motor case task, and this area is being worked only to a limited extent in the ALD and other military programs. To effectively address this significant ELV need, the potential program would contain added composite motor case technology effort as described in Section 5.3, Materials and Structures.

Coverage of the technologies for clean burning, low-cost propellant processing, and the development of non-asbestos insulation in the ongoing programs appears adequate. The problem of emergency thrust termination for solid propulsion systems is an area of concern to some of the industry. The effort would include further study of alternative solid rocket thrust termination concepts, leading to possible subsequent technology effort if promising new ideas for solution are defined.

### Low-Pressure Booster Propulsion

A number of low-pressure propulsion system alternatives, both near-term and far-term, show promise of significantly reducing ELV operating costs when compared to the higher-pressure pump-fed liquid systems and SRMs in use today. Near-term options include both liquid/liquid systems and liquid/solid hybrid systems that offer greater simplicity, thrust tailoring, thrust termination, and potentially higher performance. The liquid propellants in these systems can either be pressure-fed from pressurized tanks or pump-fed with very simple, low-pressure-rise pumps. Simpler engine component designs can reduce propulsion system costs -- e.g., one-piece metallic combustion chambers with ablative liners, composite nozzles, and much simpler injector designs. Low-weight tank pressurization concepts for the pressure-fed systems are a key technology issue, since the tanks represent a significant percentage of overall system mass.

The technology base for these systems is not as fully developed as for the systems currently in operation, although a small hybrid motor development is being pursued in a proprietary commercial venture by the American Rocket Company. Technology issues associated with both liquid/liquid and hybrid systems are being addressed in NASA's propulsion technology programs. The liquid/liquid focus is on pressure-fed applications, and the hybrid focus is on eventual application to very large (2.5 million-pound thrust range) boosters. Industry interest in using these systems in commercial launch vehicles could provide the initiative to augment ongoing programs to address technology issues unique to the ELV application. The effort would begin with system studies and selection of a system/concept approach and would progress, through analysis and code development, to subscale code evaluation and full-scale technology verification.

More innovative options, with much greater potential future payoffs, include the use of metalized gelled propellants or solid oxidizers. These approaches again offer simplicity, thrust tailoring, and thrust termination, but their higher energy density also offers compactness (increased performance in a much smaller package) that could result in significant additional cost savings. NASA and Air Force are evaluating the feasibility and true potential of these approaches in long-term research programs at low funding levels. The vehicle system studies would assess the benefits of these innovative approaches, determine the most promising concepts, and identify critical technology issues that need to be addressed for the selected concepts. If the studies generate industry interest in such systems, an appropriate technology program for the selected concepts could then be defined.

Upper Stage Propulsion

Currently operational upper stages and their respective propulsion systems include Centaur (pump-fed LOX/Hydrogen), Transtage (pressure-fed storables), Payload Assist Module (solids), and Inertial Upper Stage (IUS) (solids).

Storable propellants and solids offer only moderate performance, but provide compactness and excellent in-space storability. LOX/Hydrogen propellants offer high performance, but because of liquid hydrogen, are large in size and are difficult to store in space for lengthy periods of time.

Advanced upper stage propulsion systems, both near-term and far-term, have the potential of providing higher performance at lower cost for expendable launch vehicle applications. For example, a technology effort has been under way for a number of years and is now being brought to maturity by the development under Air Force sponsorship of a 3,750-pound thrust storable high-pressure pump-fed engine called the XLR-132. This program is planned for continuation through prototype demonstration and perhaps development. Industry is counting on continuation and completion of this ongoing effort, and additional support does not appear to be needed at this time.

An alternative storable-propellant engine could be a low-pressure pump-fed version of the pressure-fed Shuttle Orbital Maneuvering Engine. Small conventional liquid/solid hybrids are also candidates for upper stage propulsion systems, offering somewhat higher performance than currently operational systems while maintaining compactness and in-space storability. The hybrid technology efforts under way in the Low-Pressure Booster Propulsion program would be applicable to the small hybrid upper stage systems. Similarly, the more advanced metalized gelled propellants and solid oxidizers discussed above may provide significant performance enhancement for upper stage applications and can be assessed in the systems studies to determine the need for additional technology focus in this area.

## Facilities

Nationally there are a limited number of operational propulsion test facilities in government and industry. To support the ALD program and NASA's focused propulsion technology efforts in the CSTI and Exploration Technology programs it has been necessary to build a number of new facilities and to expand the capability of existing NASA and DoD facilities. Even with the new capability, some additional facilities would be required to support the propulsion portion of the potential ELV program. New test facilities for the additional technology development and verification would include component test facilities for liquid oxygen, hydrogen, and hydrocarbon turbopumps and thrust chambers, and for testing complete liquid, hybrid, and solid propulsion systems. The systems test facilities could be provided by modifying NASA facilities already in place at the Stennis, Marshall, or Lewis Centers. Some component tests may require new facilities. Provisions could be made for use of the new or modified research facilities in cooperative NASA/industry technology programs, as is done in existing test facilities.

# Materials and Structures

Industry representatives involved in ELV design, development, and production have identified a number of materials and structures technology needs. Technology needs for the U.S. government will be met by current programs such as ALD, SPIP, NASP, and the NASA and Air Force research and technology base programs. However, the industry engineers cited a number of key technology areas that may need greater emphasis. This section of the report identifies essential materials and structures technology effort that industry believes is required in addition to the current programs to provide the technology and foster the development of cost-effective ELV systems for future government and commercial launch operations.

High-priority technology needs identified for near-term applications include: expanded efforts in advanced materials and structures for low-cost cryotanks including aluminum-lithium metallic tanks and filament-wound composite structures; low-cost composite dry structures; advanced thermal protection systems; and low-cost manufacturing and processing methods. In addition, improved design/verification methodology is required for structural integrity, including launch loads and payload dynamics, to insure high reliability of future ELV structures. Longer-term needs include development of new materials, such as advanced aluminum-lithium alloys and thermoplastic composites for cryotanks, interstage and shrouds.

The following paragraphs discuss the ongoing efforts and the appropriate augmentations for each of the major materials and structures technology need areas. The effort required to develop an extensive technology base to support industry design, development, and fabrication of low-cost ELV systems for use in government and commercial operations includes: evaluation of structural concepts and trade studies; materials development; design, fabrication, and test of structural elements and subcomponents; and intermediate scale-up leading to large-scale validation.

## Structural Concepts Definition/Trade Studies

The technology efforts would begin with studies performed to identify and evaluate opportunities for ELV reduced cost and improved performance based on materials and structures technology advances and innovative concepts. Trade studies evaluate materials benefits, advanced processing and fabrication methods, innovative structural concepts, structural performance, and manufacturing costs to identify high-payoff materials and structures technologies for ELV applications. Results of these studies provide a guide for establishing technology focus and emphasis, and for identifying additional technology opportunities for follow-on activity.

## Aluminum-Lithium Cryotanks

Current ALD program efforts are focused on development, fabrication, and testing of cryotanks using existing aluminum-lithium alloy systems (ALCOA 2090, ALCAN 8090, or Reynolds Weldalite™ 049). These efforts vary in scope, but all focus on demonstrating critical cryotank technology objectives, including weldability, LOX compatibility, low-temperature performance, and fabrication of aluminum-lithium structures. The ongoing programs will provide an initial assessment of aluminum-lithium cryotank structures and a limited materials data base on current aluminum-lithium alloys, but are not directed at development of new materials with improved properties. To provide a data base on materials performance, forming, fabrication and welding, inspection, and durability sufficiently broad for scaleup to full-sized structures, additional effort may be required.

The additional effort would include the development of new aluminum-lithium materials for cryotank structures with improved weldability, formability, short transverse fracture toughness, LOX compatibility, and reduced anisotropy. The research would also expand on the current ALD program effort to focus on new aluminum-lithium alloys with improved superplastic forming capabilities for fabrication of complex structures such as isogrid reinforcement of cryotanks. It would include development of new high-temperature aluminum alloys with improved thermal resistance for high-temperature applications. These new alloy developments should lead to advanced designs with reduced structural weight and fabrication costs. Raw materials cost may also be lowered as a result of developing alternatives to Weldalite™, which is currently the only available material that is LOX-compatible.

## Composite Structures

Extensive developments in composite materials and structures have led to major applications in aeronautical vehicles. Past composites technology efforts have resulted in the development of filament-wound SRM cases for strategic missiles. NASA has recently initiated a major program in advanced composites technology for aircraft structures, which is focused on developing new materials, innovative designs, advanced design methods, low-cost fabrication, and structural test and verification of critical subcomponents. These programs will extend the existing composites design, fabrication, and production data base, and will result in major advances in composites technology. The ALD program addresses low-cost composites for ELV dry structures, including a filament-wound subscale intertank and composite shroud subcomponents using low-cost commercially available materials.

Weldalite™ -- a Martin Marietta trade mark

The potential additional effort includes the identification and development of new composite materials systems, derived from the NASA research, with the potential for low-cost processing and fabrication. One example is the ongoing NASA research in new materials for resin transfer molding. Application of these materials and fabrication methods to a broader range of ELV structures offers the potential for further cost reductions. For example, composite cryotank technology development is not considered sufficiently mature for the ALD program. The potential program provides for the development and full-scale structural testing of a composite cryotank, and for establishment of an adequate data base to facilitate industry application of the new composite materials. It would also include composite SRM case technology effort, with emphasis on smaller sizes and production cost issues.

Thermal Protection Systems

Low cost thermal protection systems (TPS) with improved environmental acceptability are being developed as part of the ALD program. One of the new TPS materials under development is a spray-on foam insulation (SOFI) with an improved blowing agent to replace the current chlorofluorocarbon material. This TPS material could provide an adequate measure of thermal protection for external tanks in existing ELV systems. Another material development is a replacement for the existing Shuttle tiles with improved toughness and durability. To optimize cost, weight, and performance, future ELV structures may require integral thermal protection systems. Advanced materials for integral TPS can provide improved performance, but will require further development and optimization.

The program would include development of new TPS for integral tank structures with internal as well as external insulation. These TPS concepts build on past research in evacuated metallic insulation, foam insulation, and hybrid systems. The additional TPS efforts would supplement the current ALD program focus on SOFI materials to provide a capability for optimum design of ELV thermal protection systems.

Advanced Processing/Fabrication Methods

Current programs in processing and manufacturing technology for composite and metallic structures have generally focused on developing new technology for low-cost fabrication. For metallic structures these programs have focused on superplastic forming, spin forming, automated welding, and in-process quality control, and have demonstrated the benefits of these technologies on panels and subcomponents using current materials systems. Composite structures programs are exploring a broader range of fabrication options with the potential for reduced cost, including filament winding, automated tape layup, pultrusion, cocuring, and thermal forming. The ALD program will demonstrate some of these techniques on selected components, such as automated assembly and welding of a 2219 aluminum cryotank dome, fabrication of small-scale aluminum lithium tanks, and filament winding of a composite intertank structure. However, additional effort is required to obtain the full benefits of these new cost-effective processing and fabrication methods for ELV applications.

The potential new effort includes development of focused advanced processing and fabrication technology for advanced aluminum-lithium cryotanks and composite cryotanks with integral metallic and non-metallic liners, fabrication of composite structures for payload shrouds with integral damping concepts, fabrication of integral TPS systems, and improved processes for automated welding, inspection, and assembly of cryotanks. Other ELV processing and fabrication requirements identified in the structural concepts definition studies can be addressed in subsequent effort.

### Integrated Data Base/Design Methods

To facilitate the application of technology to new ELV developments, the program would include establishment of an integrated design data base for materials and structures, including: design concept evaluation; design methods; materials characterization; element and subcomponent test data; details of processing, joining, environmental testing, and nondestructive evaluation; and results of materials and structures developments in the ALD and other ongoing research programs.

The design methods and design verification tasks would include development of methodology for assessment of structural integrity and life predictions of ELV structures and payloads to insure high reliability. The effort would also include the testing of dynamic scale models to verify launch and separation design loads prediction methods. New design methods such as structural tailoring for composite structures, developed in the NASA Advanced Composites Program, would be extended to ELV structures for design of innovative concepts for low-cost structures.

### Scale-Up Structural Test and Verification

The potential program includes verification of the newly developed materials and structural concepts through tests of subscale and full scale subcomponents. This level of verification is similar to the efforts planned for the ALD program and would provide the data base necessary for a full scale proof-of-concept test article. Critical components with promising potential for application in commercial ELV systems, including elements demonstrated in the ALD program, may be selected for ground testing and possibly subsequent flight testing. The potential filament-wound SRM case effort is an example of a component that would be subjected to structural test and verification.

## Facilities

Implementation of the Materials and Structures effort may require some new facilities or upgrades such as: capabilities for filament winding and automated tape layup of composite cryotanks, and advanced interstage and payload shroud designs; thermal structures testing facilities for composite and metallic cryotanks to verify new materials and TPS concepts; and laboratory capabilities to develop advanced aluminum-lithium and high-temperature aluminum materials for launch vehicle applications. The existing and new facilities would be suitable for use in cooperative NASA/industry research.

SECTION 5.4

## Avionics and Operations

NASA's R&T Base and the ALD program contain efforts directed at autonomous, adaptable, and fault-tolerant avionics systems to increase reliability, safety, and flexibility, and to reduce cost. The ongoing programs also include technology for reduction of operations manpower, time, and cost. However, opportunity exists for additional avionics and operations technology that can benefit both government and commercial ELVs. Moreover, the industry inputs indicate that flight validation to reduce the risk of new technology application is a particularly important consideration for ELV avionics.

The potential effort discussed in this section, covering both expendable earth-to-orbit and orbital-transfer vehicles, would complement the ongoing programs by providing additional avionics and operations technology specifically directed at ELVs and suitable for practical utilization. It would include near-term application of existing technology as well as high-payoff new technology for the future.

The effort would involve considerable systems study and economic modeling effort, in conjunction with the ELV industry, to identify and evaluate cost drivers and the effects of potential near-term and future technology advances.

### Guidance and Control for Upper Winds Loading Relief

Advanced guidance and control could permit real-time adjustment to wind dispersions, potentially eliminating much of the pre-launch manual flight planning and trajectory design procedures which increase launch operations uncertainty, cost, and time. The ALD program includes an effort directed at technology that will enable a next-generation launch vehicle to carry out a sophisticated form of guidance based on onboard light detection and ranging (LIDAR) measurement of atmospheric conditions ahead of the vehicle. Ongoing NASA programs are developing air data sensor technology and wind profile measurement systems which will provide an essential capability for a variety of guidance and control systems for advanced manned launch systems.

The additional effort would be directed at a control system which utilizes the NASA-developed ground-based wind profile measurement system upgraded as necessary, a communications link with the ELV, and ALD or new onboard algorithms to keep the vehicle within prescribed load limits. Such an approach would be suitable for incorporation in incremental and block changes on existing ELV systems.

Early flight testing would be conducted on a small launch vehicle or sounding rocket, or as a self-contained payload on an existing ELV or Shuttle. Following the definition of ELV guidance and control requirements, the onboard algorithms and system performance necessary to satisfy the launch vehicle attitude and trajectory constraints would be established. The necessary software and hardware would then be defined and developed, including onboard computers and ground support elements. Integrated testing would be performed to ensure that the system meets all requirements as a test article for use in the validation flight test program.

Next-Generation Fault-Tolerant Avionics

Considerable effort in government and industry programs is being devoted to the development of technology for fault-tolerant avionics systems. Technology being addressed in the ALD program and in some of the NASA research is directly relevant to ELVs. Commercial ELV economic factors, however, may suggest different reliability criteria and thus different solutions for commercial ELVs than those dictated by unmanned military mission success or human safety considerations for manned flight.

To assess the impact of fault-tolerant avionics technology on expendable vehicle ground and flight operations, and to determine the fault-tolerant avionics features most important and appropriate to ELV systems from a standpoint of total system cost, performance, and reliability, the program would include cost model development and cost-benefit analyses. The analytical process would include the synthesis of a representative ELV avionics workload for use in assessing performance and reliability of candidate fault-tolerant architectures. It also includes definition and evaluation of a conceptual optimized fault-tolerant avionics system for application specifically to ELVs to identify associated technology requirements.

A closely related technology of potential importance to the ELV industry is that of formal verification (i.e., design proof) for avionics systems. Formal verification is a process of mathematically proving that each step of the design process is consistent with previous steps and with the original specification. Its objective is to eliminate design flaws and common mode failures early in the design process, where change is the least expensive. It involves the use of formal specification languages, mathematical logic, semi-automatic theorem provers, and other tools not yet fully developed. Formal verification is not sufficiently mature for application to an entire avionics system. To further the development of the technology for ELV application, the effort would include selection of at least one critical subsystem from the candidate fault-tolerant avionics system definition to be subjected to formal verification. This would involve the formulation of formal specifications and proof of successive hardware and software design steps -- where possible, empirically verifying proof assumptions and constraints in controlled experiments.

## Photonics Technology for Far-Term Flight-Crucial Systems

Optical technology can be applied to aerospace system architectures and components and offers the advantages of inherent parallelism leading to high data rates, lower power, weight, and size requirements for a given computational or technological capability, resistance to electromagnetic and high-energy radio-frequency interference, and a higher degree of fault tolerance. Photonic systems have fewer discrete active components and physical connections than electronic systems, and optical architectures are generally more resistant to single-component failures. Photonic technology could eventually be used throughout the launch vehicle for data acquisition, high-speed communications, and rapid information extraction and analysis. Finally, digital and analog optical systems can be used for high-speed onboard computing, including data analysis.

Currently, component technology is being pursued in the OAET R&T Base programs, with the Fiber Optics Rotation Sensor being representative of the most advanced technology. The ALD program is pursuing a laser-initiated pyrotechnic device to reduce both the hazard and the ground processing cost associated with ELV active ordnance devices. Exploration Technology program plans include a photonics initiative involving optical processor architectures and algorithms, spatial light modulator development, and fiber optic networks. Focused photonics efforts are also planned under aeronautics R&T programs.

Photonics technology specifically directed at ELVs is not contemplated. However, ongoing aeronautics, space, and exploration technology efforts would be monitored so that results can be utilized in the ELV systems studies where appropriate, and focused ELV photonics effort can be implemented when progress warrants separate emphasis.

## Integrated Electromechanical Actuators, Power, and Controls

Progress is being made in a number of government and industry programs on integrated electromechanical actuators (EMAs), power, and control systems -- a technology of considerable potential benefit to ELVs. The resultant elimination of hydraulics, auxiliary power units, and ground support carts and equipment offers promise of major improvements in launch vehicle economy, dispatch reliability, safety, and servicing, test, and operational efficiencies. These benefits have been quantified in several aircraft and space systems studies, including studies showing pre-launch testing savings of thousands of manhours for Atlas/Centaur launch vehicles and even greater savings for the Space Shuttle.

The promise of improved performance using EMAs is currently being demonstrated in cruise missiles, and EMAs have been tested successfully in several flight and laboratory experiments. The ALD program includes ground demonstration of large (25 to 50 horsepower) actuators. The focus of the potential program effort is on adapting the EMA technology to machines in the 1 to 5 horsepower and 5 to 20 horsepower sizes and conducting flight tests on current-generation ELVs.

The effort would begin with development of performance and operational requirements for integrated EMAs, high-frequency electrical power systems, intelligent control, and built-in test equipment (BITE). It would then proceed to fabrication, integration, and flight test of an experimental actuator/motor/controller combination including the remote checkout provisions.

## Automated Ground and Launch Operations

The application of automation to ELV systems has the potential for reducing manpower needs, improving safety and performance, increasing reliability, and reducing turnaround times and costs. Advanced flight vehicles rely heavily on software to accomplish their missions. The cost of designing, developing, testing, and maintaining avionics software is becoming an increasingly large part of total life-cycle cost. Discussions with industry indicated that new software engineering technologies will be introduced incrementally. For example, it would probably not be feasible to use new methods to reengineer software in existing ELVs. However, many aspects of testing and validation could be automated. Advances such as automation of communication between ELV data bases could reduce operational costs and turnaround time, eliminate reentry of duplicate data, eliminate the need to track duplicate data across multiple data bases for maintenance purposes, and facilitate transfer of data between data bases.

The ALD and the CSTI programs and the OSF's advanced development programs contain activity directed at the application of state-of-the-art expert systems and robotics technology to advanced operations. Among its cost-reduction activities, the ALD program includes an effort to improve the software development environment. It is tailored to new system development and ALS architecture specifics, and may not be applicable to existing ELV families or to the variety of new ELV developments, advanced computer architectures, and parallel processors to be anticipated in the future.

The CSTI Automation and Robotics (A&R) program includes activities to demonstrate the use of expert systems for real-time fault detection in Shuttle flight operations and the application of artificial intelligence (AI) and robotics to streamline ground operations. Additionally, this program is developing new generic technologies having broad aerospace applications, including efforts related to learning, planning and scheduling, intelligent assistants, intelligent agents, and large knowledge-based systems.

The additional effort on this subject would be intended to facilitate the transition of ALD and CSTI automation technology to the ELV industry. It would include automation technology for software development, operations, and training, as applied both to specific near-term and generic future expendable vehicles. The objective would be to develop technology advances which could be implemented at various stages in the progress of the vehicle programs -- some requiring no significant modification, some appropriate for incorporation during major block changes, and some feasible only in new development.

The effort would start with a series of studies to develop system models as a basis for definition of technology needs for automation of future systems. For several existing ELVs, studies would examine launch operations requirements, software needs, and cost drivers, to define the system architecture and technology requirements for an integrated automated system capable of supporting development, maintenance, and operation of all of the software and hardware associated with preflight, flight, and ground support. The studies would include the identification of areas in which operations might be simplified, for commercial operations, by elimination of requirements solely related to unique government mission or operational considerations. Although the studies might identify opportunities for application of some automation benefits to existing ELV families in the near term, the primary purpose would be analysis and integration of the individual system definitions to support definition of a generic ELV system for use in identifying new technology needs for future automated systems.

The software technology portion of the effort would apply specifically to ELVs the benefits of two promising new software engineering approaches currently under evaluation for ALS application -- Computer-Aided Software Engineering, and software reusability. It would include the development of requirements, concepts, methodologies, and tools for an integrated software environment workstation for use by the industry to support the automation of software development and maintenance processes and software reuse in ELV development.

NASA has been developing Intelligent Computer-Aided Training systems, and planning and scheduling systems based on expert systems technology, for use in Shuttle and other government programs to achieve improvements in economy, reliability, and safety by automating the operations personnel training process and the planning and scheduling processes. The program would include efforts to facilitate the application of these technologies -- e.g., knowledge-based interactive training systems -- to ELV operations.

## Test Capabilities

NASA program offices, in conjunction with the ALD program, are currently considering two new capabilities which could be of considerable value to the ELV industry.

An avionics productivity center is being considered as a mechanism to facilitate the transition of new avionics technology into launch vehicle development. At present, schedule and cost risks involved in space-qualifying new technology can in some instances deter the application of available technology. The purpose of the center would be to permit verification of hardware and software technology in a simulated flight environment prior to actual vehicle use. If such a productivity center is appropriate, the U.S. government would work with industry to provide practical protected use by industry, either in cooperative government/industry component and subsystem technology programs or in proprietary commercial development efforts on a reimbursable basis. These provisions could include, for example, the definition of ELV-industry-unique requirements, the development of industry ELV simulation software, and the addition of company-secure hot bench experiment processing facilities and work stations to enable ELV industry test and evaluation of new software and hardware in a systems environment.

The other potentially valuable new capability being considered is an automated operations and management testbed, a laboratory intended to permit experimentation, validation, and evaluation of automated operations hardware and software in high-fidelity launch support simulation. The primary purpose of the testbed would be to provide an off-line but realistic laboratory environment in which automation and robotics researchers can work together with engineers and technicians experienced in real-world operational support activity. The culture of ground operations has evolved over a long period of time and has proven largely successful, albeit manpower-intensive and time-consuming. If the automation and robotics technology being generated in the universities and research laboratories is eventually to be incorporated in actual practice, it must be guided not only by the academic and research community but also by the experienced hands-on operators as well. Here also, if the testbed is developed for use in government and university R&T programs, additional features could be provided for convenient and, if necessary, proprietary utilization by industry.

SECTION 5.5

## Resources

The potential program reported herein is intended to supplement relevant R&T Base, CSTI, Exploration Technology, and ALD programs -- the primary ongoing technology efforts to improve U.S. government and commercial launch capabilities. The President's Fiscal Year 1991 NASA budget requests about $55 million for technology and $40 million for ALD propulsion development efforts. The funding requirements for implementation of the potential program would depend on the status of those ongoing programs and the extent of cost-sharing approaches with industry based on industry's commitment to such a program. In some areas, funding requirements would be determined on the basis of program details defined following system studies conducted to identify the major technology cost drivers. The additional efforts identified in the report have not been funded, based upon ongoing assessments of relative priority vis-a-vis the existing programs.

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APPENDIX A

# Near-Term Assistance to Industry

The long-term viability of the nation's commercial ELV industry may be decided in the marketplace in the near term (3 to 5 years), rather than by long-term strategies. Recognizing this, NASA asked the ELV and satellite industry, through the Department of Transportation's COMSTAC, to respond to the following question:

> "What can NASA do to aid the domestic commercial launch vehicle and satellite industry in the increasingly competitive international marketplace from 1990 and beyond?"

The objective was to identify what NASA might do in the near term to aid the commercial ELV and satellite industry both by technology developments and policy/administrative actions that could lower cost or increase reliability. Emphasis is placed on cost and reliability since, although they are not the only factors considered in the selection of a launch service or a satellite, they are dominant factors.

The COMSTAC response suggested near-term technology developments that could result in early adoption by the commercial ELV industry. However, the COMSTAC noted that technology development, indeed, development of new commercial launch vehicles, by their foreign competitors are government funded.

The COMSTAC reports that the European Space Agency (ESA) is developing a brand new ELV, Ariane V, along with the associated launch complex infrastructure. The planned investment is $4 to 5 billion with an objective of reducing launch costs 40 percent. China and Japan have launch vehicle development programs under way. However, the domestic commercial ELV industry must capitalize the adoption of new technologies and amortize these costs within their launch service price. According to the COMSTAC, the ESA and China fund their ELV development cost, while their commercial marketing entities bear only the incremental launch services costs.

Table A-1 summarizes the COMSTAC's suggestions of near-term policy and administrative actions that the government should continue or initiate to maintain or improve the industry's competitive posture in international markets. Many of these suggested policies and administrative actions are currently in place while others need renewed emphasis or clarification.

In response to policy directives, NASA, like the Air Force, has developed use agreements that provide private sector ELV operators access to NASA property and services. NASA has instituted a two-tier commercial use





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agreements process. Headquarters agreements specify the general terms and conditions under which ELV operators may use NASA ELV property and services. In addition, the Headquarters enabling agreements authorize industry to negotiate sub-agreements with the appropriate NASA field centers for use of specific NASA property and services. Table A-2 lists the status of both Headquarters agreements and field center sub-agreements.

NASA property/services will be provided to the commercial ELV community on a non-interference, cost-reimbursable basis. NASA services will only be provided to the commercial industry, if the requisite services are not available from the private sector.

Four NASA Headquarters Commercial Use Agreements have been signed to date with General Dynamics, McDonnell Douglas, Martin Marietta, and LTV Aerospace. Four additional Agreements are currently in negotiation with Orbital Sciences Corporation, American Rocket Company, E'Prime Aerospace, and TRW.

Kennedy Space Center (KSC) has three signed Sub-agreements with McDonnell Douglas, Martin Marietta, and General Dynamics. The KSC/General Dynamics sub-agreement was an important milestone, since it was the first NASA Commercial Use sub-agreement and since it allowed General Dynamics to take over the operations and maintenance responsibility for the Atlas/Centaur launch complex at Cape Canaveral Air Force Station. Goddard Space Flight Center (GSFC) has signed a sub-agreement with McDonnell Douglas to provide technical transition support of their first four commercial Delta launches. Marshall Space Flight Center (MSFC) has signed a sub-agreement with Martin Marietta to support acoustic testing of the commercial Titan III. The Office of Space Operations (OSO) has signed a sub-agreement with McDonnell Douglas to provide support of NASA's ground-based tracking and data stations to the commercial Delta program. Approximately seven additional Subagreements are in various stages of negotiation with industry. In addition, NASA has consummated Commercial Use Agreements with both Space Services, Inc. and Conatec for support to commercial sub-orbital operations at GSFC's Wallops Flight Facility (WFF).

In addition to COMSTAC's ideas noted above, the OSF has identified several actions that could also assist the ELV commercial community. These are:

- Establish an ad hoc task team with members of the COMSTAC with the charter to assess the near-term policy and administrative suggestions offered by the COMSTAC (Table A-1) and the OSF. A consolidated action plan agreed to by both the ad hoc industry team and NASA would be approved by the NASA Associate Administrator for the Office of Space Flight. This action plan would define the steps necessary to bring to resolution or closure each suggestion or initiative. In some cases, Congressional consultation or action may be required.

- The OSF to serve as an advocate within NASA for the operational commercial ELV community. The OSF will work to ensure the ELV community is kept apprised of NASA activities and developments in a timely manner. Specifically:

  - Continue to encourage the use of NASA's operational test facilities/services to the commercial ELV industry. The NASA Office of Commercial Programs publication entitled, Accessing Space, describes some of these in greater detail.

  - Provide to industry, upon request, technical teams of ELV discipline experts to critique new vehicle designs, new operational procedures, etc. For example, Orbital Sciences Corporation invited NASA to attend and participate in the critical design review of the Pegasus launch vehicle. Also provide technical teams to participate in the initial Flight Readiness Reviews of new launch vehicles and vehicle configurations.

  - Assist industry in the acquisition of launch sites and design of launch and payload processing facilities that would allow industry to be independent to the maximum extent feasible of U.S. Government programs where there are threats of U.S. Government preemptive disruptions of commercial operations.

  - Where feasible, facilitate the flight test of promising new ELV technology applications on U.S. Government missions without jeopardizing mission success.

- Initiate a program of small, low cost space payloads. These payloads could be proof of science or technology applications concepts attendant with the acquisition of promising new small class ELV launch services. The launch services, like the payloads, would serve to test and demonstrate new ELV technologies, where such technologies do not overly compromise mission success. NASA could provide flight opportunities for small low cost/high risk scientific, application or technology payloads, and could procure commercial launch services for these satellites on a competitive basis. The launch service selection criteria could emphasize low cost, innovativeness, and flexibility, rather than a probability of mission success exceeding the 96 percent norm expected for NASA's small and medium performance class launch services. Offerors on NASA's flight opportunity launch services could be encouraged to propose and demonstrate new technology components that promise lower cost or higher reliability. NASA may from time-to-time piggyback new technologies on its missions. These proof-of-concept demonstrations of new technologies could certify designs before commitment to in-line performance or mission success.

POLICY

- NASA sponsor U.S. commercial ELV technology developments.
  - establish equivalent of NACA Aeronautics Model Program
  - focus on cost reduction and reliability enhancements
  - oversee integration of new technologies into vehicle
- Procure U.S. Government civil launch services from domestic commercial ELV operators, whenever possible.
- Provide long-term contractual commitments for launch services.
- Provide support to the nonrecurring development tasks associated with implementing new component technologies into vehicle.
- Eliminate U.S. Government's preemptive rights in shared facilities.
- NASA develop a new efficient, low cost, reliable ELV in the 6000 to 10000 pound performance range to Geotransfer orbit.

ADMINISTRATIVE

- Prior to solicitation for research, development or technology projects, undertake a review of existing private activities in that area to assure it does not duplicate privately funded work.
- NASA conduct cooperative flight test programs of new technology applications.
- Provide on-going access to NASA's libraries, research facilities, and real-time access to test data.
- Improve access to technologies owned by the U.S. Government, particulary DoD.
- Add emphasis on joint endeavors and perhaps direct subsidies to attract technologies that may become markets of the future.
- Consider restructuring NASA to split R&D from operations.
- NASA become permanent interface with the Air Force at the launch ranges for all civilian launch vehicles and satellites.
- Rigorously enforce trade agreements with foreign ELV competitors.
- Formally institutionalize commercial ELV procurement practices.
  - eliminate cost and pricing data certification
  - allow commercial payment schedules
  - delete Federal Acquisition Regulation requirements not appropriate in commercial procurements.
  - relax data and oversight requirements consistent with a commercial program.

Table A-1 Summary of COMSTAC's Suggested Near-Term ELV Policy and Administrative Actions

| COMPANY | HEADQUARTERS - UMBRELLA | | CENTER - SUBAGREEMENT | | |
|---|---|---|---|---|---|
| | STATUS | CONTENT | CENTER | STATUS | CONTENT |
| GENERAL DYNAMICS (Atlas I/II) | March 1987 | Use of Production Tooling, STE, GSE/ Launch Service Support | KSC | March 30, 1988 | • GD - O&M of Complex 36<br>• Use of Launch Support Services |
| | Modification 1 November 1988 | Incl Use of Facilities | LeRC | Draft In Review | • Use Of Technical Support |
| McDONNELL DOUGLAS (Delta II) | September 1988 | Use of Launch Support Services | KSC | December 13, 1988 | • Use of Support Services (Payload Processing) |
| | | | KSC/ VAFB | In Negotiation | • Use of SLC-2 and Support Services |
| | | | GSFC | December 22, 1988 | • Use of Technical Transition Support |
| | | | OSO | April 28, 1989 | • Use of OSO Resources, Principally GSFC, Code 500 |
| MARTIN MARIETTA (Titan III) | October 1988 | Use of Launch Support Services | KSC | March 16, 1989 | • Use of Support Services (Payload Processing/ Encapsulation) |
| | | | MSFC | May 2, 1989 | • Use of Acoustic Test Facilities |
| LTV (Scout) | November 1988 | Use of Production Tooling, STE, GSE/ Launch Service Support | GSFC/ WFF | Draft In Work | • Use of Real Property<br>• Use of Range Safety/ Range &Support Services |
| | | | LaRC | GSFC Concurrence Rev. | • Use of GSE, Production Tooling STE |
| | | | KSC/ VAFB | Preliminary Discussions | • Use of Facilities/Support Services |
| ORBITAL SCIENCES (Pegasus/ Taurus) | Final Signature Cycle - On Hold | Use of Launch Support Services/ Facilities | GSFC/ WFF | Draft in Review | • Use of Facilities/Support at WFF |
| | | | ARC/ DFRF | Draft in Review | • Use of Facilities/Support at DFRF/Use of NASA B-52 |
| AMERICAN ROCKET (Industrial L.V.) | First Draft | Use of Launch Support Services/ Facilities | TBD | TBD | TBD |
| E' PRIME (E'PAC) | First Draft | Use of Support Services/Facilities | KSC | Preliminary Discussions | • Use of Facilities/Support Services at ETR |
| TRW (TBD) | First Draft | Use of Property/Services | GSFC/WFF | Preliminary Discussions | TBD |
| | | | SSC | Preliminary Discussions | • Use of Test Facilities |

Table A-2 NASA ELV Commercialization Agreements as of June 1990

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APPENDIX B

# ELV Procurement Details and Vehicle Descriptions

## Air Force

For the CELV program, Martin Marietta was awarded a ten-vehicle Titan IV contract. In addition, Martin Marietta was given a contract to modify eight Titan IIs. Following the Challenger and Titan accidents, the Titan IV program was expanded to provide 23 vehicles with west-coast launch capability and with launch rate capability increased from two to six per year.

The McDonnell Douglas MLV contract provides for the acquisition of 20 Delta II vehicles with unpriced options for additional vehicles through 1994.

The General Dynamics MLV II contract provides for the acquisition of two Atlas II vehicles with options for up to eight per year through 1995.

## NASA

Under the mixed fleet launch strategy, four Shuttle payloads were rescheduled for ELV launches. They are the Roentgen Satellite, Extreme Ultraviolet Explorer, Combined Release and Radiation Effects Satellite, and Mars Observer.

The 1988 launch services contract to General Dynamics was to support the launch of two firm and three optional NOAA GOES satellites. Other commercial launch services and launch vehicles being procured include:

- Small ELV: NASA plans to award an SELV launch services contract in 1990 for seven firm and three optional launches to support the scientific Small Explorer Program.
- Medium ELV: The MELV contract being negotiated with McDonnell Douglas will provide for launch services for three firm and twelve optional Delta II launches to support NASA scientific and technology applications spacecraft.
- Intermediate ELV: A proposal to provide launch services for the scientific Solar Heliospheric Observatory is currently under evaluation with a contract award targeted for the Spring of 1990. A request for proposals to procure launch services commercially to support the Mobile Satellite spacecraft is targeted for release in the Spring of 1990.

- Large ELV: NASA plans will require an average of one Titan IV per year from the Air Force beginning in 1995 to support major scientific planetary and observatory missions.

## Vehicle Descriptions

The General Dynamics Atlas family of vehicles is based on modifications of the NASA Atlas/Centaur vehicle introduced in 1967, which was an evolutionary development of the Air Force 1950s Atlas ICBM. The Atlas, a two and one-half stage vehicle, is powered by oxygen/ hydrocarbon (RP-1) engines; the Centaur is powered by oxygen/ liquid-hydrogen engines.

- Atlas I is an improved version of NASA's Atlas/Centaur compatible with a larger (14-foot diameter) payload fairing.
- Atlas II builds on the Atlas I configuration to provide increased performance capability -- most notably, increased booster engine thrust and lengthened propellant tanks.
- Atlas IIA is similar to Atlas II but incorporates an uprated RL-10 propulsion system and upgraded avionics.
- Atlas IIAS builds on Atlas IIA with the addition of four Castor IVA solid rockets for increased performance capability.

The McDonnell Douglas Delta II is an upgraded version of NASA's Delta launch vehicle which was originally derived from the Air Force Thor intermediate-range ballistic missile, with improved first and second stages and the addition of several small SRMs. Delta II has two configurations; the first configuration has upgraded strap-on motors and the second configuration includes upgraded composite-case SRMs. Both configurations are available in either two or three stages and include a 12-foot propellant tank stretch and a bulbous payload fairing.

The Martin Marietta Titan III launch vehicle is the company's variant of the Air Force Titan III/34D family first launched in 1966. It is based on a common Titan design concept featuring a two-stage, liquid-propellant, 10-foot-diameter core vehicle with two strap-on SRMs.

Titan IV is a non-commercial stretched, strengthened development of Titan III with a new payload fairing diameter designed to accommodate Shuttle-compatible payloads. Titan IV has three versions: one with no upper stage, one with an IUS, and one with Centaur.

APPENDIX C

# Acronym List

| | |
|---|---|
| A&R | Automation and Robotics |
| AI | Artificial Intelligence |
| ALS | Advanced Launch System |
| ALD | Advanced Launch Development |
| ARC | Ames Research Center |
| BITE | Built-in Test Equipment |
| CELV | Complementary Expendable Launch Vehicle |
| CFD | Computational Fluid Dynamics |
| COMSTAC | Commercial Space Transportation Advisory Committee |
| CSTI | Civil Space Technology Initiative |
| CTP | Chemical Transfer Propulsion |
| DFRF | Dryden Flight Research Facility |
| DoD | Department of Defense |
| DoT | Department of Transportation |
| ELV | Expendable Launch Vehicle |
| EMA | Electromechanical Actuator |
| ESA | European Space Agency |
| ETO | Earth-to-Orbit |
| ETR | Eastern Test Range |
| GD | General Dynamics |
| GOES | Geostationary Operational Environmental Satellite |
| GPS | Global Positioning Satellite |
| GSE | Ground Support Equipment |
| GSFC | Goddard Space Flight Center |
| ICBM | Intercontinental Ballistic Missile |
| IELV | Intermediate Expendable Launch Vehicle |
| IUS | Inertial Upper Stage |
| KSC | John F. Kennedy Space Center |
| LaRC | Langley Research Center |
| LeRC | Lewis Research Center |
| LIDAR | Light Detection and Ranging |
| LOX | Liquid Oxygen |
| MELV | Medium Expendable Launch Vehicle |
| MLV | Medium Launch Vehicle |
| MSFC | George C. Marshall Space Flight Center |
| NACA | National Advisory Committee for Aeronautics |
| NASA | National Aeronautics and Space Administration |
| NASP | National AeroSpace Plane |
| NOAA | National Oceanographic and Atmospheric Administration |
| O&M | Operations and Maintenance |
| OAET | Office of Aeronautics, Exploration and Technology |

# Acronym List

| | |
|---|---|
| OSF | Office of Space Flight |
| OSO | Office of Space Operations |
| P.L. | Public Law |
| SELV | Small Expendable Launch Vehicle |
| SOFI | Spray-on Foam Insulation |
| SPIP | Solid Propulsion Integrity Program |
| SRM | Solid Rocket Motor |
| SLC | Space Launch Complex |
| SSC | Stennis Space Center |
| STE | Special Test Equipment |
| R&D | Research and Development |
| R&T | Research and Technology |
| TBD | To Be Determined |
| TPS | Thermal Protection System |
| VAFB | Vandenberg Air Force Base |
| WFF | Wallops Flight Facility |